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C6 GPMG and 40 mm AGL weapon integrated on RWS mounted on TAPV platform

Probability of hit methodology

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Defence R&D Canada – Valcartier
Contract Report
DRDC Valcartier CR 2010-237
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Abstract

A probability of hit (PHit) methodology has been developed to characterize the overall performance of the C6 General Purpose Machine Gun (GPMG) and 40 mm Automatic Grenade Launcher (AGL) Integrated on a Remote Weapon Station (RWS) Mounted on a Tactical Armoured Patrol Vehicle (TAPV) Platform. The methodology takes into account four (4) different scenarios (static/moving vehicle to engage a static/moving target) to develop an error budget of the weapon system.

The error budget analysis breaks down the total dispersion, i.e., the standard deviation (SD) of the impact point position, into four (4) main error sources: weather, gun, projectile and the Fire Control System (FCS) Dispersion. The weather dispersion can be developed to see the individual contributions of the standard deviation of the wind speed, atmospheric temperature and atmospheric pressure. The Gun dispersion can be developed to see the individual contributions to the standard deviation of the gun support and the gun barrel. The projectile dispersion can be developed to see the individual contributions to the standard deviation of the ammunition dispersion, muzzle velocity, drag-mass ratio and tracer effect. The FCS dispersion can be developed to see the individual contributions to the standard deviation of the gun laying, target tracking, vehicle movement and mutual interaction effects.

The PRODAS (PROjectile and Design and Analysis System) budget error and simulation package were used to model the weapon system performance for different firings conditions. The experimental data from the static/moving vehicle against static/moving target scenarios necessary to validate the PRODAS modeling is being obtained in the CFB (Canadian Forces Base).

Résumé

Une méthodologie de probabilité d’impact (PHit) a été développée pour caractériser la performance globale de la mitrailleuse polyvalente (GPMG) C6 et du lanceur automatique de grenade (AGL) 40 mm intégrés sur un système d’armement télécommandé (RWS) monté sur un véhicule de patrouille blindé tactique (TAPV). La méthodologie prend en considération quatre (4) scénarios différents (véhicule statique/en mouvement qui engage une cible statique/en mouvement) pour le développement du budget d’erreur du système d’arme.

L’analyse du budget d’erreur décompose la dispersion totale, soit la déviation standard (SD) de la position du point d’impact, en quatre (4) principales sources d’erreur : Météo, l’arme, projectile et le système de conduite de tir (FCS). La dispersion météo peut être développée pour analyser les différentes contributions individuelles de la déviation standard de la vitesse du vent, de la température atmosphérique et de la pression atmosphérique. La dispersion de l’arme peut être développée pour analyser les différentes contributions individuelles de la déviation standard du support et de l’âme de l’arme. La dispersion du projectile peut être développée pour analyser les différentes contributions individuelles de la déviation standard de la dispersion de la munition, de la vitesse initiale du projectile, du rapport traînée-masse et l’effet du traceur. La dispersion du FCS peut être développée pour analyser les différentes contributions individuelles de la déviation

standard du support de l’arme, du système de pointage de l’arme, le mouvement du véhicule et les effets d’interactions mutuelles.

L’ensemble numérique de simulation et de calcul du budget d’erreur PRODAS (PROjectile and Design and Analysis System) ont été utilisés pour la modélisation de la performance du système d’armement pour différentes conditions de tirs. Les données expérimentales provenant des scénarios véhicule statique/en mouvement qui engage une cible statique/en mouvement nécessaires pour valider la modélisation PRODAS seront obtenus à la BFC (Base des Forces canadiennes).

Executive summary

C6 GPMG and 40 mm AGL weapon integrated on RWS mounted on TAPV platform: Probability of hit methodology

; DRDC Valcartier CR 2010-237; Defence R&D Canada – Valcartier; September 2010.

The Tactical Armoured Patrol Vehicle (TAPV) is a general-utility combat vehicle that will fulfill a wide variety of roles on the battlefield, including but not limited to reconnaissance and surveillance, security, command and control, cargo and armoured personnel carrier. It will have a high degree of tactical mobility and provide a very high degree of protection to its crew. The TAPV is a high-priority procurement project of the Canadian Forces (CF) aiming to replace the capabilities of the Coyote, RG-31 and increase the Light Utility Vehicle Wheeled (LUVW) fleet. The TAPV will integrate a Remote Weapon Station (RWS), which shall be capable of mounting two (2) weapons simultaneously (dual RWS). At time of Request for Proposal (RFP) closing, the dual RWS shall be capable of mounting a 40 mm Automatic Grenade Launcher (AGL) as a primary weapon and a C6 (7.62 mm) General Purpose Machine Gun (GPMG) as a secondary weapon. The TAPV dual RWS shall be operable by the crew commander and gunner from their respective crew stations inside the vehicle.

A probability of hit (PHit) methodology has been developed to characterize the overall performance of the C6 GPMG and 40 mm AGL Integrated on a RWS mounted on a TAPV Platform. The methodology takes into account four (4) different scenarios (static/moving vehicle to engage a static/moving target) to develop an error budget model of the weapon system. The error budget analysis breaks down the total dispersion (standard deviation of the impact point position) into four (4) main error sources: weather, gun, projectile and the Fire Control System (FCS) dispersion. The weather dispersion can be developed to see the individual contributions of the standard deviation of the wind speed, atmospheric temperature and atmospheric pressure. The Gun dispersion can be developed to see the individual contributions of the standard deviation of the gun support play and the gun barrel. The projectile dispersion can be developed to see the individual contributions of the standard deviation of the ammunition dispersion, muzzle velocity, drag mass ratio and tracer effect. The fire control system dispersion can be developed to see the individual contributions of the standard deviation of the gun laying, target's tracking, vehicle movement and mutual interaction effects.

The PRODAS (PROjectile and Design and Analysis System) budget error and simulation package were used to model the weapon system performance for different firing conditions. The experimental data from the static/moving vehicle against static/moving target scenarios necessary to validate the PRODAS modeling is being obtained in the CFB (Canadian Forces Base). The main difficulties are to characterise the target tracking, vehicle movement and mutual interaction effect. These effects need to take into account the vehicle, gunner and RWS interaction effect on the weapon accuracy. Also, the RWS does not have a wind speed and direction sensor to take into account the weather effect on the accuracy. In addition, the driver and gunner experience can have a significant influence on the overall weapon system. All these effects need to be approximated to be able to characterize the realistic weapon performance.

Sommaire

C6 GPMG and 40 mm AGL weapon integrated on RWS mounted on TAPV platform: Probability of hit methodology

; DRDC Valcartier CR 2010-237; R & D pour la défense Canada – Valcartier; Septembre 2010.

Le véhicule de patrouille blindé tactique (TAPV) est un véhicule de combat d'utilité générale qui répondra à une grande variété de rôles sur le champ de bataille, incluant mais sans se limiter à la reconnaissance et la surveillance, la sécurité, le commandement et contrôle, fret et transport de troupes blindé. Il aura un degré élevé de mobilité tactique et fournira un très haut degré de protection à son équipage. Le TAPV est un projet d'acquisition de haute priorité pour les Forces canadiennes, qui a pour but de remplacer les capacités du Coyote, RG-31 et augmenter les flottes de Véhicule utilitaire léger à roues (LUVW). Le TAPV intégrera un système d'armement télécommandé (RWS) qui sera capable de recevoir le montage de deux (2) armes simultanément (double RWS). Au moment de la clôture de la demande de proposition (RFP), le double RWS devra être capable de monter un lanceur automatique de grenades (AGL) 40 mm comme arme primaire et un C6 (7.62 mm), mitrailleuse polyvalente (GPMG) comme arme secondaire. Le TAPV avec double RWS devra pouvoir être opéré par le commandant d'équipage et le canonnier à partir de leurs stations respectives de l'équipage à l'intérieur du véhicule.

Une méthodologie de probabilité d'impact (PHit) a été développée pour caractériser la performance globale de la C6 et du lanceur automatique de grenade 40 mm (AGL) intégrés sur un RWS monté sur un TAPV. La méthodologie prend en considération quatre (4) scénarios différents (véhicule statique/en mouvement qui engage une cible statique/en mouvement) pour le calcul du facteur erreur. Le calcul du budget d'erreur décompose la dispersion totale (déviation standard de la position du point d'impact) en quatre (4) principales sources d'erreur : météo, canon, projectile et le système de conduite de tir. La dispersion météo peut être développée pour analyser les différentes contributions individuelles de la déviation standard de la vitesse du vent, température atmosphérique et pression atmosphérique. La dispersion du canon peut être développée pour analyser les différentes contributions individuelles de la déviation standard du support à canon et le l'âme du canon. La dispersion du projectile peut être développée pour analyser les différentes contributions individuelles de la déviation standard de la dispersion de la munition, vitesse initiale, rapport traînée masse et effet du traceur. La dispersion du système de conduite de tir peut être développée pour analyser les différentes contributions individuelles de la déviation standard du pointage du canon, poursuite de cibles, mouvement du véhicule et effet d'interaction mutuel.

Le budget d'erreur et programme de simulation PRODAS (PROjectile and Design and Analysis System) ont été utilisés pour modéliser la performance du système d'arme dans des conditions différentes de tirs. Les données expérimentales provenant des scénarios véhicule statique/en mouvement qui engage une cible statique/en mouvement nécessaires pour valider la modélisation PRODAS seront obtenus à la BFC (Base des Forces canadiennes). Les principales difficultés sont de caractériser le suivi de la cible, le mouvement du véhicule et l'effet de l'interaction mutuelle. Ces effets doivent prendre en considération l'effet d'interaction du véhicule, canonnier et du RWS sur la précision de l'arme. Aussi, le RWS n'a pas d'anémomètre ni de capteur de

direction pour prendre en considération l’effet de la météo sur la précision. De plus, l’expérience du conducteur et du canonnier peut avoir une influence significative sur la performance globale de l’arme. Tous ces effets ont besoin d’être approximés pour être en mesure de caractériser une performance réaliste de l’arme.

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1 Introduction

The Tactical Armoured Patrol Vehicle (TAPV) is a general-utility combat vehicle that will fulfill a wide variety of roles on the battlefield, including but not limited to reconnaissance and surveillance, security, command and control, cargo and armoured personnel carrier. It will have a high degree of tactical mobility and provide a very high degree of protection to its crew. The TAPV will replace the capabilities of the Coyote, RG-31 and increase the Light Utility Vehicle Wheeled (LUVW) fleet.

The TAPV will integrate a Remote Weapon Station (RWS), which shall be capable of mounting two (2) weapons simultaneously (dual RWS). At time of Request for Proposal (RFP) closing, the dual RWS shall be capable of mounting a 40mm automatic grenade launcher (AGL) as a primary weapon and a C6 (7.62 mm) general purpose machine gun as a secondary weapon. The TAPV dual RWS shall be operable by the crew commander and gunner from their respective crew stations inside the vehicle.

The C6 provided will be one of the in-service Canadian Forces (CF) weapons. It is unknown at this time which 40 mm AGL will be the weapon that is awarded through the Close Area Suppression Weapon System (CASW) project. However, for the purpose of this task given that it will be an in-service weapon, the CASW technical data can be used as a benchmark or reference.

2 Objectives & Requirements

The objective of this report is to provide a methodology to obtain the ammunition PHit of the C6 GPMG and 40 mm AGL weapons, integrated on a RWS mounted on a TAPV platform to be used within the Statement of Operational Requirements (SOR) and in turn translated into Vehicle Performance Specifications (VPS) for the TAPV project [1]. This methodology requires development for:

Identifying error sources

Modeling a budget error for different scenarios

- Static TAPV versus static target
- Static TAPV versus moving target
- Moving TAPV versus static target
- Moving TAPV versus moving target

Input process into PRODAS numerical tools

From this study, future fire tests could be reviewed to improve the overall requirements and procedures.

3 Methodology

In support to CASW project, error budget modeling in PRODAS has already been used with success in previous studies at DRDC Valcartier for accessing performance of 40 mm AGL for static weapon against static target scenario [2],[3],[4]. In the present study, to identify the main error sources for evaluation of the overall performance of the C6 GPMG and 40 mm AGL Integrated on a RWS mounted on a TAPV Platform, the methodology has been slightly modified to take into account the particularity of the weapon system and the different operational scenarios.

This study was developed in three (3) sections: Error source, Error Budget and PRODAS Simulation Package [5]. The first section describes all error sources and their inter-relation required to characterize the weapon system. The second section identifies the methodology to resolve the budget error for each scenario (static/moving vehicle to hit a static/moving target). The last section presents the PRODAS Simulation Package used to simulate PHit of the weapon system.

3.1 Error source

A multitude of error sources have been identified to support the PHit modeling of the weapon system for various scenarios. The block diagram presented in Figure 1 show a dispersion analysis used in this study.

In general, the dispersion errors presented in this report will require two (2) independent components, since they can be different in the azimuth and elevation planes. Nonetheless, some comments will be added if the azimuth and elevation planes require a different analysis. Each error is defined in a one-sigma standard deviation and the unit used is mils. The mils unit is defined by a deviation of 1 meter at a distance of 1000 m and is approximately equal to 1 mrad. Equation (1) shows the relation between mils and mrad:

$$\frac{1\mathrm{m}}{1000\mathrm{m}} = 1\,\mathrm{mils} \approx \tan^{-1}\left(\frac{1}{1000}\right)\mathrm{rad} \approx 0.001\,\mathrm{rad} = 1\,\mathrm{mrad} \qquad (1)$$

Also, some parameters require a statistic analysis of the experimental data. Equations (2) and (3) show the average and the standard deviation equations respectively:

$$\bar{x} = \frac{\sum_{i=1}^{N} x_i}{N} \qquad (2)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i - \bar{x}\right)^2}{N-1}} \qquad (3)$$

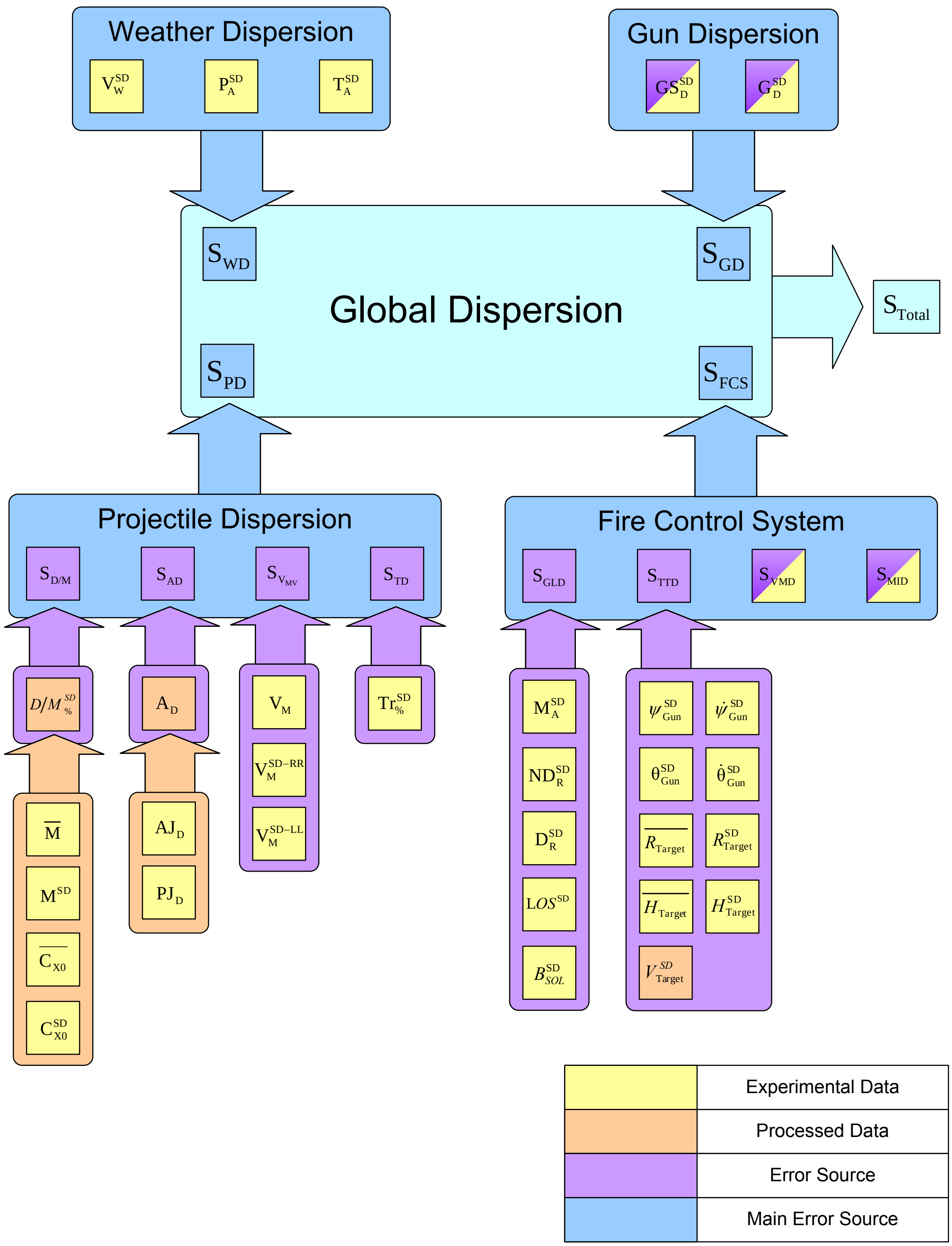

Figure 1: Dispersion analysis block diagram.

3.1.1 Global dispersion

The global dispersion is the standard deviation of the projectile impact about the mean point of impact (MPI). This parameter needs to be evaluated for each round fired. Table 1 shows the global dispersion parameter.

Table 1: Global dispersion parameter.

Symbol	Unit	Description
S_{Total}	mils	Global dispersion (SD of the impact points)
X^{SD}_{Total}	meter	SD of the impact points

Experimentally, the global dispersion (S_{Total}) represents the standard deviation of the impact points measured (X^{SD}_{Total}) on the target azimuth and elevation planes. The standard deviation is calculated with equation (3) on all impact points. The global dispersion can be evaluated in mils by equation (4), where $\overline{R}_{Target}$ is the average target's range in meter.

$$S_{Total} = 1000 \cdot \tan^{-1}\left(\frac{X^{SD}_{Total}}{\overline{R}_{Target}}\right) \tag{4}$$

Theoretically, the global dispersion can be obtained by equation (5), where the global dispersion equals the root of the square summation of the four (4) different dispersion subsections, which are the Weather, Gun, Projectile and Fire Control System:

$$S_{Total} = \sqrt{S^2_{PD} + S^2_{GD} + S^2_{WD} + S^2_{FCS}} \tag{5}$$

Equations (4) and (5) are similar for the azimuth and elevation planes, but their values can be different.

3.1.2 Weather dispersion

The weather dispersion corresponds to the standard deviation (SD) error of the average atmospheric conditions. This parameter is considered as an occasion-to-occasion error. However, in the case where the weather conditions are unstable during the entire trials, the analysis of this dispersion might be considered as a round-to-round error. Table 2 shows the global weather dispersion and atmospheric parameters.

Table 2: Weather dispersion parameters.

Symbol	Unit	Description
S_{WD}	mils	Weather dispersion (SD of the error of the weather along the trajectory)
S_{V_W}	mils	Wind speed dispersion (SD of the error of the average wind speed along the trajectory)
V_W^{SD}	m/s	SD of the error of the average wind speed along the trajectory
S_{P_A}	mils	Atmospheric pressure dispersion (SD of the error on the atmospheric pressure at gun site)
P_A^{SD}	mbar	SD of the error on the atmospheric pressure at gun site
S_{T_A}	mils	Atmospheric temperature dispersion (SD of the error on the atmospheric temperature at gun site)
T_A^{SD}	°C	SD of the error on the atmospheric temperature at gun site

Experimentally, the atmospheric parameters (wind speed, pressure and temperature) are measured simultaneously along the projectile path from two (2) (or more) meteorological stations. In this case, each standard deviation is calculated with equation (3). At this point, it is difficult to define the weather dispersion effect (S_{WD}) without a simulation analysis. The simulation analysis needs to take into account a multitude of parameters and requires numerical modeling such as implemented in the PRODAS software described later in section 3.3.

The weather dispersion can be approximated with the root of the square difference between the global dispersion and the global dispersion without the weather effect. This solution has the goal to extract only the weather effect of the global dispersion. Equation (6) shows the process to obtain the weather dispersion, which is used by the PRODAS software.

$$S_{WD} = \sqrt{\left(\underbrace{f_{PRODAS}\left(V_W^{SD}, P_A^{SD}, T_A^{SD}\right)}_{\substack{\text{global dispersion} \\ \text{with the weather effect}}}\right)^2 - \left(\underbrace{f_{PRODAS}\left(V_W^{SD}\Big|_0, P_A^{SD}\Big|_0, T_A^{SD}\Big|_0\right)}_{\substack{\text{global dispersion} \\ \text{without th e weather effect}}}\right)^2} \qquad (6)$$

Equation (6) is the same for the azimuth and elevation planes, but their values can be different. In addition, the same procedure can be reused three (3) times to separate only the wind speed (S_{V_W}), pressure (S_{P_A}) or temperature (S_{T_A}) dispersion effect. The weather dispersion can be obtained at this time by equation (7).

$$S_{WD} = \sqrt{S_{V_W}^2 + S_{P_A}^2 + S_{T_A}^2} \qquad (7)$$

3.1.3 Gun dispersion

The overall gun dispersion is a round-to-round error and it is the component of the dispersion attributed to the gun support play and gun barrel. The gun support play dispersion corresponds to the looseness of the fixed gun on its support and the RWS assembly itself. The gun dispersion is the dispersion exclusively due to the barrel. Table 3 shows the general gun dispersion parameters.

Table 3: Gun dispersion parameters.

Symbol	Unit	Description
$\mathrm{S_{GD}}$	mils	Gun Dispersion (SD of the overall Gun Dispersion)
$\mathrm{X}_{GD}^{\mathrm{SD}}$	meter	SD of the overall gun barrel head position
$\mathrm{S_{GSP}}$	mils	Gun Support Play Dispersion (SD of the Gun Support Play Dispersion)
$\mathrm{S_{GB}}$	mils	Gun Barrel Dispersion (SD of the Gun Barrel Dispersion)

3.1.3.1 **Overall gun dispersion**

Experimentally, the overall gun dispersion ($\mathrm{S_{GD}}$) represents the standard deviation of the overall gun barrel head position ($\mathrm{X}_{GD}^{\mathrm{SD}}$) during the fire trials on the target azimuth and elevation planes. The standard deviation is obtained with equation (3) on the overall gun barrel head position. The gun barrel head position is evaluated usually with two (2) perpendiculars high-speed videos (side and top views). The overall gun dispersion can be evaluated in mils with equation (8), where $D_{\mathrm{M/RWS}}$ is the distance between the RWS elevation axis and the barrel muzzle exit.

$$\mathrm{S_{GD}} = 1000 \cdot \tan^{-1}\left(\frac{\mathrm{X}_{GD}^{\mathrm{SD}}\Big|_{\mathrm{With\ Fire\ Trials}}}{D_{\mathrm{M/RWS}}} \right) \tag{8}$$

Also, equation (9) shows that the overall gun dispersion can also be obtained by the root of the square summation of the dispersion of the gun support and gun.

$$S_{GD} = \sqrt{\left(S_{GSP}\right)^2 + \left(S_{GB}\right)^2} \tag{9}$$

3.1.3.2 Gun dispersion

Experimentally, the gun barrel dispersion (S_{GB}) represents the standard deviation of the gun barrel head position during the fire trials on the target azimuth and elevation planes. However, the weapon needs to be rigidly fixed to the ground to take into account only the gun barrel dispersion effect without any support and RWS mechanical play. This procedure requires that the same gun has to be used.

3.1.3.3 Gun support play dispersion

Theoretically, gun support play dispersion can be approximated with the root of the square difference between the overall gun dispersion and the gun barrel dispersion. This solution has the goal to extract only the gun support and the RWS mechanical play effects of the overall gun dispersion. Equation (10) shows the process to obtain the gun support play dispersion:

$$S_{GSP} = \sqrt{\left(S_{GD}\right)^2 - \left(S_{GB}\right)^2} \tag{10}$$

Experimentally, the maximum gun support play dispersion can be directly approximated by an evaluation of the gun support play limits without the fire trials. In this case, the methodology consists to evaluate of the maximum overall gun barrel head position (with the initial position as reference), when the gunner moves manually the muzzle exit in the limits of the gun support and the RWS mechanical play. However, this procedure doesn't take into account the RWS and TAPV effects during the firing. The gun support dispersion can be evaluated in mils by equation (11), where $D_{\mathrm{M/RWS}}$ is the distance between the RWS rotation axis and the barrel muzzle exit.

$$S_{GSP} = 1000 \cdot \tan^{-1}\left(\frac{X_{GD}^{\mathrm{Maxium}}\Big|_{\mathrm{Without\ Fire\ Trials}}}{D_{\mathrm{M/RWS}}} \right) \tag{11}$$

Equations (8), (9), (10) and (11) are the same for the azimuth and elevation planes, but their values can be different.

3.1.4 Projectile dispersion

The projectile dispersion can be a round-to-round error and an occasion-to-occasion error. It is the component of the dispersion attributed to the muzzle gun properties and ammunition flight-out. Table 4 shows the general projectile dispersion parameters.

Table 4: Projectile dispersion parameter.

Symbol	Unit	Description
S_{PD}	mils	Projectile Dispersion (SD of the Projectile Dispersion)

Experimentally, the projectile dispersion represents the standard deviation of the projectile during the flight-out. However, the projectile dispersion can't be obtained directly from the experimental data. Thus, the projectile dispersion is a summarized value and is obtained analytically to characterize the muzzle gun properties and ammunition flight-out. Equation (12) shows that the projectile dispersion is obtained by the root of the square summation the four (4) different dispersion subsections as: ammunition, muzzle velocity, drag/mass effect and tracer effect.

$$S_{PD} = \sqrt{S_{AD}^2 + S_{V_{MV}}^2 + S_{D/M}^2 + S_{TD}^2} \tag{12}$$

Equation (12) is the same for the azimuth and elevation planes, but their values can be different.

3.1.4.1 Ammunition dispersion

The ammunition dispersion is a round-to-round error and is the component of the dispersion attributed to the ammunition shell from a fixed mount. Table 5 shows the general ammunition dispersion parameters.

Table 5: Ammunition dispersion parameters.

Symbol	Unit	Description
S_{AD}, A_D	mils	Ammunition Dispersion (SD of the Overall Ammunition Dispersion.)
PJ_D	mils	SD of the Projectile jump
AJ_D	mils	SD of the Aerodynamic jump

Experimentally, the ammunition dispersion represents the standard deviation of the projectile jump and the aerodynamic jump using the “Mann Barrel” on a fix mount. The aerodynamic jump can be calculated with the linear theory of ballistic using the first maximum yaw measured from an aeroballistics’ range trial. The projectile jump can be also calculated with an effect of a center of gravity (offset from a projectile x-axis). Both jumps are determined by the analytical equations shown in section 3.3.1.3. The ammunition dispersion is defined by the magnitude of the previous combined effects shown by equation (13).

$$S_{AD} = A_D = \sqrt{PJ_D^2 + AJ_D^2} \tag{13}$$

Equation (13) is the same for the azimuth and elevation planes and their values are also the same for both planes.

3.1.4.2 **Muzzle velocity dispersion**

The muzzle velocity dispersion corresponds to the standard deviation of the error of the muzzle velocity effect. This analysis takes into account the round-to-round error and the occasion-to-occasion error into two (2) different parameters. Table 6 shows the general muzzle velocity dispersion and parameters.

Table 6: Muzzle velocity dispersion parameters.

Symbol	Unit	Description
$S_{V_{MV}}$	mils	Muzzle Velocity Dispersion (SD of overall muzzle velocity effect)
V_M	m/s	Reference muzzle velocity at 21 °C
V_M^{SD-RR}	m/s	SD of muzzle velocity within a lot of ammunition at 21 °C (round-to-round error)
V_M^{SD-LL}	m/s	SD of muzzle velocity between lots of ammunition at 21 °C (occasion-to-occasion error)

Experimentally, the reference muzzle velocity is an average value measured and deduced from Doppler radar tests. From these values, the standard deviations of the muzzle velocity are defined with equation (3) for the projectile within a lot and between lots of ammunition. At this point, it is difficult to define only the muzzle velocity dispersion effect ($S_{V_{MV}}$) without a simulation analysis. The simulation analysis needs to take into account a multitude of parameters and requires a software simulation such as PRODAS as described in section 3.3. The muzzle velocity dispersion can be approximated with the root of the square difference between the global dispersion and the global dispersion without the weather error effect. This solution has the goal to extract only the muzzle velocity effect of the global dispersion. Equation (14) shows the process to obtain the muzzle velocity dispersion, which is used by the PRODAS software simulation.

$$S_{WD} = \sqrt{\left(\underbrace{f_{PRODAS}\left(V_M^{SD-RR}, V_M^{SD-LL}\right)}_{\substack{\text{global dispersion} \\ \text{with the muzzle velocity effect}}}\right)^2 - \left(\underbrace{f_{PRODAS}\left(V_M^{SD-RR}\Big|_0, V_M^{SD-LL}\Big|_0\right)}_{\substack{\text{global dispersion} \\ \text{without th e muzzle velocity effect}}}\right)^2} \tag{14}$$

Equation (14) is the same for the azimuth and elevation planes, but their values can be different. In addition, the same procedure can be reused two (2) times to separate the muzzle velocity dispersion effect of the projectile within a lot and between lots of ammunition.

3.1.4.3 Drag/Mass dispersion

The Drag/Mass dispersion is a round-to-round error and corresponds to the standard deviation of the error of the projectile drag and mass percentage ratio. Table 7 shows the general drag/mass dispersion and parameters.

Table 7: Drag/Mass dispersion parameters.

Symbol	Unit	Description
$S_{D/M}$	mils	Drag/Mass Dispersion (SD of Drag/Mass percentage ratio)
$D/M_{\%}^{SD}$	%	SD of Drag Mass percentage ratio
$\overline{M}$	kg	Average of the mass of projectile
M^{SD}	kg	SD of the mass of projectile
$M_{\%}^{SD}$	%	Percentage of the SD of the mass of projectile
$\overline{C_{X0}}$		Average of the drag coefficient of projectile (Average of the axial force coefficient)
C_{X0}^{SD}		SD of the drag coefficient of projectile (SD of the axial force coefficient)
$C_{X0_{\%}}^{SD}$	%	Percentage of the SD of the drag coefficient of projectile

The drag error is the variation of the drag coefficient (axial force coefficient) over the trajectory. It is essentially a result of the shape reproduction/tolerance and the non-uniform rotating band ware. Experimentally, the drag coefficient of the projectile (C_{X0}) is obtained from the velocity Doppler radar trace measured over the trajectory. Equation (15) shows the relation to obtain the axial force coefficient form the velocity Doppler radar trace, where M is the projectile mass, ρ_A is the atmospheric air density, A_{ref} is the projectile reference area and V is the projectile velocity:

$$C_{X0} = \frac{\left({}^{dV}\!/_{dt}\right)\mathrm{M}}{1/2\ \rho_{\mathrm{A}}\mathrm{A}_{\mathrm{ref}}\mathrm{V}^2} \tag{15}$$

From equation (15), the average and standard deviations of the drag coefficient ($\overline{C_{X0}}, \mathrm{C}_{X0}^{\mathrm{SD}}$) is defined with equations (2) and (3) at each Mach number on the overall projectiles fired. The average and the standard deviations of the projectile mass ($\overline{\mathrm{M}}, \mathrm{M}^{\mathrm{SD}}$) are calculated with equations (2) and (3) on the overall projectiles fired. At this point, it is difficult to define only the Drag/Mass dispersion effect ($S_{\mathrm{D/M}}$) without a simulation analysis. The simulation analysis needs to take into account a multitude of parameters and requires a software simulation such as PRODAS as described in section 3.3. The Drag/Mass dispersion can be approximated with the root of the square difference between the global dispersion and the global dispersion without the Drag/Mass error effect. This solution has the goal to extract only the Drag/Mass effect of the global dispersion. Equations (16) and (17) show the process to obtain the Drag/Mass dispersion, which is used by the PRODAS software simulation and $D/M_{\%}^{SD}$ is a specific PRODAS parameter to define the percentage of the standard deviation of Drag/Mass ratio.

$$D/M^{SD} = \frac{\mathrm{C}_{X0}^{\mathrm{SD}}}{\overline{\mathrm{M}}} - \frac{\overline{C_{X0}}}{\overline{\mathrm{M}}^2}\mathrm{M}^{\mathrm{SD}} \tag{16}$$

$$\mathrm{S}_{\mathrm{D/M}} = \sqrt{\left(\underbrace{f_{\mathrm{PRODAS}}\left(D/M_{\%}^{SD}\right)}_{\substack{\text{global dispersion} \\ \text{with the Drag/Mass effect}}}\right)^2 - \left(\underbrace{f_{\mathrm{PRODAS}}\left(D/M_{\%}^{SD}\big|_0\right)}_{\substack{\text{global dispersion} \\ \text{without th e Drag/Mass effect}}}\right)^2} \tag{17}$$

Equation (17) is the same for the azimuth and elevation planes, but their values can be different.

3.1.4.4 **Tracer dispersion**

The tracer dispersion is a round-to-round error and corresponds to the standard deviation of the error of the projectile tracer. Table 8 shows the general tracer dispersion and parameter.

Table 8: Tracer dispersion parameters.

Symbol	Unit	Description
S_{TD}	mils	Tracer Dispersion (SD of the tracer)
$\overline{\mathrm{Tr}}$		Average of the thrust coefficient of projectile (Average of the axial force coefficient)
Tr^{SD}		SD of the tracer
$\mathrm{Tr}_{\%}^{SD}$	%	Percentage of SD of the tracer

The tracer error is the variation of the drag coefficient (or axial force coefficient or retard) over the trajectory when the tracer is active. It is essentially a result of the tracer powder mass tolerance and the gun barrel temperature interaction during the combustion. Experimentally, the tracer coefficient of the projectile (Tr) is approximated from the difference of the velocity Doppler radar trace measured between the active and without tracer effect over the trajectory. Equation (18) shows the relation to obtain the tracer coefficient of the projectile (Tr) from the active tracer effect (C_{X0}^{AT}) and without the tracer effect (C_{X0}^{WT}):

$$\mathrm{Tr} = \underbrace{C_{X0}^{AT}}_{\text{Active Tracer}} - \underbrace{C_{X0}^{WT}}_{\text{Without Tracer}} \tag{18}$$

Equation (19) shows the relation to obtain the tracer coefficient of the active tracer effect (C_{X0}^{AT}) that can be obtained by the axial force coefficient from the velocity Doppler radar trace, when the tracer is active. M is the projectile mass, $\mathrm{M_P}(t)$ is the tracer powder mass as function of time, ρ_A is the atmospheric air density, $\mathrm{A_{ref}}$ is the projectile reference area and V is the projectile velocity:

$$C_{X0}^{AT} = \frac{\left(dV/dt\right)\left[\mathrm{M} + \mathrm{M_P}(t)\right]}{1/2\ \rho_A \mathrm{A_{ref}} \mathrm{V}^2} \tag{19}$$

Equation (20) shows the relation to obtain the tracer coefficient without tracer effect (C_{X0}^{WT}) that can be obtained by the axial force coefficient from the velocity Doppler radar trace, when the tracer doesn't have the tracer powder. M is the projectile mass, ρ_{A} is the atmospheric air density, $\mathrm{A}_{\mathrm{ref}}$ is the projectile reference area and V is the projectile velocity:

$$C_{X0}^{\mathrm{WT}} \frac{\left(dV \big/ dt \right) [\mathrm{M}]}{1/2\, \rho_{\mathrm{A}} \mathrm{A}_{\mathrm{ref}} \mathrm{V}^2} \tag{20}$$

From equation (18), the average and standard deviations of the drag coefficient ($\overline{\mathrm{Tr}}$, $\mathrm{Tr}^{\mathrm{SD}}$) are defined with equations (2) and (3) at each Mach number on the overall projectiles fired. At this point, it is difficult to define only the tracer dispersion effect (S_{TD}) without a simulation analysis. The simulation analysis needs to take into account a multitude of parameters and requires a software simulation such as PRODAS described in section 3.3. The tracer dispersion can be approximated with the root of the square difference between the global dispersion and the global dispersion without the tracer error effect. This solution has the goal to extract only the tracer effect of the global dispersion. Equations (21) and (22) show the process to obtain the tracer dispersion, which is used by the PRODAS software simulation. $\mathrm{Tr}_{\%}^{\mathrm{SD}}$ is a specific PRODAS parameter to define the percentage of the standard deviation of the tracer.

$$\mathrm{Tr}_{\%}^{\mathrm{SD}} = \frac{\mathrm{Tr}^{\mathrm{SD}}}{\overline{\mathrm{Tr}}} \tag{21}$$

$$\mathrm{S}_{\mathrm{TD}} = \sqrt{\left(\underbrace{f_{\mathrm{PRODAS}} \left(\mathrm{Tr}_{\%}^{\mathrm{SD}} \right)}_{\substack{\text{global dispersion} \\ \text{with the tracer effect}}} \right)^2 - \left(\underbrace{f_{\mathrm{PRODAS}} \left(\mathrm{Tr}_{\%}^{\mathrm{SD}} \Big|_0 \right)}_{\substack{\text{global dispersion} \\ \text{without th e tracer effect}}} \right)^2} \tag{22}$$

Equation (22) is the same for the azimuth and elevation planes, but their values can be different.

3.1.5 Fire Control System dispersion

The FCS dispersion is an occasion-to-occasion error. It is the component of the dispersion attributed to the alignment, aiming, target's tracking and vehicle movement errors. For a RWS mounted on TAPV platform, the fire control system is considered as a black box, where the performances are evaluated on the overall system. The performance of the system can be evaluated without the gunner interaction, since for a perfect system it has always the human factor. For this reason, the fire control system (black box) takes into account the driver and the gunner interaction. For this analysis, the fire control system dispersion is broken into four (4) different effects to observe a specific overall effect and will be shown in the following sections. However, each effect can be broken also in other source effects, but the analysis can become a difficult and long process. Table 9 shows the general fire control system dispersion parameter.

Table 9: Fire Control System dispersion parameter.

Symbol	Unit	Description
S_{FCS}	mils	Fire Control System Dispersion

Experimentally, the FCS dispersion represents the standard deviation of the projectile dispersion attributed to the gun laying, tracking target and vehicle movement errors. However, the fire control system dispersion can't be obtained directly from the experimental data and an analysis is required to extract the fire control system dispersion. Equation (23) shows that the fire control system dispersion is obtained by the root of the square summation of the four (4) different dispersion subsections as: gun laying, target's tracking, vehicle movement and mutual interaction.

$$S_{FCS} = \sqrt{S_{GLD}^2 + S_{TTD}^2 + S_{VMD}^2 + S_{MID}^2} \tag{23}$$

Equation (23) is the same for the azimuth and elevation planes, but their values can be different.

3.1.5.1 Gun laying dispersion

The gun laying dispersion is an occasion-to-occasion error and corresponds to the standard deviation of the error of the gun mainly due to the fire control system, display and the gunner aim interpretation. Table 10 shows the general gun laying dispersion and parameters.

Table 10: Gun laying dispersion parameters.

Symbol	Unit	Description
$\mathrm{S}_{\mathrm{GLD}}$	mils	Standard Deviation of the Gun Laying Dispersion
$\mathrm{X}_{\mathrm{GL}}^{\mathrm{SD}}$	meter	Standard Deviation of the gun laying position
$\mathrm{M}_{\mathrm{A}}^{\mathrm{SD}}$	mrad	Misalignment error of FCS with gun (Boresight Error)
$\mathrm{D}_{\mathrm{R}}^{\mathrm{SD}}$	mrad	Display resolution error
$\mathrm{ND}_{\mathrm{R}}^{\mathrm{SD}}$	mrad	Night/day resolution error
$\mathrm{L}OS^{\mathrm{SD}}$	mrad	Line of sight stability error
B_{SOL}^{SD}		Ballistic FCS solution error

Experimentally, the gun laying dispersion represents the standard deviation of the gun alignment attributed to a gunner's fire control system interaction and the gun alignment in the case where the target and gunner is static. At this point, it is difficult to define each component effect of the overall gun laying dispersion effect ($\mathrm{S}_{\mathrm{GLD}}$) without a complex process analysis. For this reason, the gun laying dispersion can be approximated with the standard deviation of the final gun barrel head position, when the gunner requires aiming at a fixed point on the target before the firing. The standard deviation is obtained with equation (3) on the final gun barrel head position ($\mathrm{X}_{\mathrm{GL}}^{\mathrm{SD}}$). The gun barrel head position is usually evaluated with two (2) perpendiculars videos (side and top views). The gun laying dispersion can be evaluated in mils by equation (24), where $D_{\mathrm{M/RWS}}$ is the distance between the RWS rotation axis and the barrel muzzle exit.

$$S_{GLD} = 1000 \cdot \tan^{-1}\left(\frac{X_{GLD}^{SD}\Big|_{\text{Without Fire Trials}}}{D_{M/RWS}}\right) \tag{24}$$

Equation (24) is the same for the azimuth and elevation planes, but their values can be different. This approach takes into account the boresight error, display resolution error, night/day resolution error, line of sight stability error and the misalignment error of FCS with gun. However, the ballistic FCS solution error (difference between the fire control system and the experimental ballistic solution) assumes that it has no dispersion effect and has only a bias from the predicted mean point of impact. In this case, the bias will be taken into account during the boresight procedure and doesn't have any effect on the gun laying dispersion.

Theoretically, the gun laying dispersion can be approximated by the static-static budget error resolution shown in section 3.2.1. The procedure consists to extract the gun laying effect (S_{GLD}) from the global dispersion (S_{Total}) by subtracting all known effects (S_{WD}, S_{GD} and S_{PD}).

3.1.5.2 **Target's tracking dispersion**

The target's tracking dispersion (or aiming error) is an occasion-to-occasion error and is the component of the dispersion attributed to the gun, mainly from a mechanical aspect and gunner interaction. In the remote weapon station, the gunner can choose two (2) different options: auto or manual tracking. However, depending on each option, the aiming concept can be difficult to characterize and is dependant on the gunner's experience. Table 11 shows the general target tracking dispersion and parameters.

Table 11: Target's tracking dispersion parameters.

Symbol	Unit	Description
S_{TTD}	mils	Standard Deviation Target's Tracking Dispersion
θ_{Gun}^{Error}	deg	Cant angle error of gun mounts in the azimuth plane
$\dot{\psi}_{Gun}$	rad/s	The angular velocity of the cant angle of gun mounts in the azimuth plane
$\dot{\psi}_{Gun}^{SD}$	rad/s	Standard Deviation of the angular velocity of the cant angle of gun mounts in the azimuth plane
V_{Target}^{SD}	meter/s	Standard Deviation in the average relative target velocity
$\overline{R_{Target}}$	meter	The average target range
R_{Target}^{SD}	meter	Standard Deviation of the error of the target range.
$\overline{H_{Target}}$	meter	The average target base altitude
H_{Target}^{SD}	meter	Standard Deviation of the error knowing the target base altitude.

Experimentally, the target's tracking dispersion represents the standard deviation of the gun alignment attributed to a gunner's fire control system interaction to aim a moving target. However, it is difficult experimentally to define only the target's tracking dispersion effect. Figure 2 shows the main target's tracking difficulty to evaluate the standard deviation in the average relative target velocity.

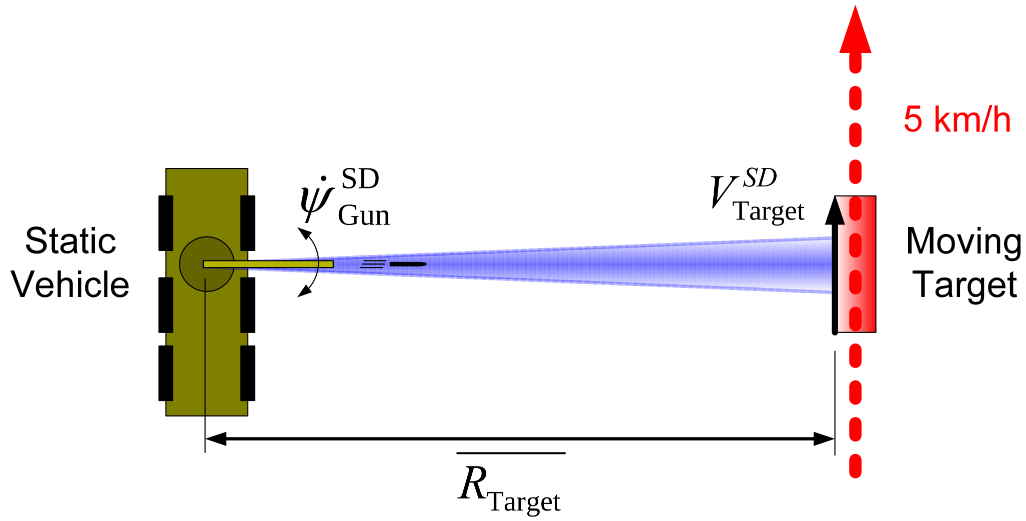

Figure 2: Representation of the standard deviation of the relative target velocity.

This process requires evaluating the standard deviation of the angular velocity cant of the gun mounts in an azimuth plane to track a moving target on a static vehicle. The standard deviation of the angular velocity is obtained by the error between the experimental and the theoretical angular velocity cant of gun mounts in the azimuth plane to track a moving target on a static vehicle. From this value, Equation (25) shows the process to obtain the approximation of the standard deviation of the average relative target velocity.

$$V^{SD}_{\mathrm{Target}} = \overline{R_{\mathrm{Target}}}\,\dot{\psi}^{\mathrm{SD}}_{\mathrm{Gun}} + R^{\mathrm{SD}}_{\mathrm{Target}}\,\dot{\psi}_{\mathrm{Gun}} \tag{25}$$

The simulation analysis needs to take into account a multitude of parameters and requires a software simulation such as PRODAS as described in section 3.3. The target's tracking dispersion can be approximated with the root of the square difference between the global dispersion and the global dispersion without the target's tracking error effect. This solution has the goal to extract the only target's tracking effect of the global dispersion. Equation (26) shows the process to obtain the target's tracking dispersion, which is used by the PRODAS software simulation.

$$\mathrm{S}_{\mathrm{TTD}} = \sqrt{\left(\underbrace{f_{\mathrm{PRODAS}}\left(R^{SD}_{\mathrm{Target}}, H^{SD}_{\mathrm{Target}}, V^{SD}_{\mathrm{Target}}, \theta^{\mathrm{Error}}_{\mathrm{Gun}}\right)}_{\text{global dispersion with the target's tracking effect}}\right)^2 - \left(\underbrace{f_{\mathrm{PRODAS}}\left(R^{SD}_{\mathrm{Target}}\Big|_0, H^{SD}_{\mathrm{Target}}\Big|_0, V^{SD}_{\mathrm{Target}}\Big|_0, \theta^{\mathrm{Errc}}_{\mathrm{Gun}}\right.}_{\text{global dispersion without t he target's tracking effect}}} \tag{26}$$

Equation (26) is the same for the azimuth and elevation planes, but their values can be different. In addition, the same procedure can be reused four (4) times to separate the target range, altitude, average relative target velocity and cant angle dispersion effect.

Theoretically, the target's tracking dispersion can be approximated by the static-moving budget error resolution shown in section 3.2.2. The procedure consists to extract the target's tracking effect (S_{TTD}) from the global dispersion (S_{Total}) by subtracting all known effects (S_{WD}, S_{GD}, S_{PD} and S_{GLD}).

3.1.5.3 Vehicle movement dispersion

The vehicle movement dispersion is an occasion-to-occasion error and is the component of the dispersion attributed to the vehicle from a road/land aspect and driver interaction. For a remote weapon station, the gun can be stabilized on 1 or 2 axis. However, depending of the environment, the vehicle movement concept can be difficult to characterize and usually will have a large dependency with the road/land aspect. Table 11 shows the general vehicle movement dispersion parameter.

Table 12: Vehicle movement dispersion parameter.

Symbol Unit		Description
S_{VMD}	mils	Vehicle Movement Dispersion

Experimentally, the vehicle movement dispersion represents the standard deviation of the gun alignment attributed to the vehicle suspension, road/land type and the driver's abilities. However, it is difficult to define the vehicle movement dispersion effect without a complex analysis. Nonetheless, the vehicle movement dispersion can be approximated theoretically by the moving-static budget error resolution shown in section 3.2.3. The procedure consist to extract the vehicle movement effect (S_{VMD}) from the global dispersion (S_{Total}) by subtracting all known effects (S_{WD}, S_{GD}, S_{PD}, S_{GLD} and S_{TTD}).

3.1.5.4 **Mutual interaction dispersion**

The mutual interaction dispersion is a round-to-round error and is the component of the dispersion attributed to the driver and gunner interaction. For a remote weapon station, the gunner can increase the vehicle movement dispersion in the case where gunner has difficulty to take into account the relative velocity between the vehicle and the target. However, depending of the environment, the mutual interaction error can be difficult to characterize and usually will have a large dependency with the gunner's aiming. Table 13 shows the general mutual interaction dispersion parameter.

Table 13: Mutual interaction dispersion parameter.

Symbol Unit		Description
S_{MID}	mils	Mutual Interaction Dispersion

Experimentally, the mutual interaction dispersion represents the standard deviation of the gun alignment attributed to the gunner's abilities to take into account the relative velocity between the vehicle and the target. In the best case, the target's tracking and the vehicle movement effect will characterize the overall engagement dynamic and thus, the mutual interaction effect will tend to zero (always positive). However, it is difficult to define the mutual interaction movement dispersion effect without a complex analysis. Nonetheless, the mutual interaction dispersion can be approximated theoretically by the moving-moving budget error resolution shown in section 3.2.4. The procedure consist to extract the mutual interaction effect (S_{MID}) from the global dispersion (S_{Total}) by subtracting all known effects (S_{WD}, S_{GD}, S_{PD}, S_{GLD}, S_{TTD} and S_{VMD}).

3.2 Error budget

The budget error has the goal to index the overall effect with the same unit. The budget error gives also the possibility to observe the direct impact of each effect on the global dispersion and at the same time to complete or to deduce the unknown values. For the following budget error, each effect error can be different in the azimuth and elevation planes. In this case, all errors presented will require two (2) different balances for the azimuth and elevation planes. However, both cases use exactly the same methodology and for this reason, this section will be showing only the general balance. Table 14 shows each error source taken into account in the budget error.

Table 14: Error budget.

Dispersion Effect			Azimuth Plane	Elevation Plane
S_{Total}				
	S_{GD}			
		S_{GSP}		
		S_{GB}		
	S_{WD}			
		S_{V_W}		
		S_{P_A}		
		S_{T_A}		
	S_{PD}			
		S_{AD}		
		$S_{V_{MV}}$		
		$S_{D/M}$		
		S_{TD}		
	S_{FCS}			
		S_{GLD}		
		S_{TTD}		
		S_{VMD}		
		S_{MID}		

To fill the budget error, multitudes of data are required, which can come from various sources such as experimental data, analytical study and also maybe a guest value. In this study, the data came from four (4) different scenarios where a static/moving vehicle was engaging a

static/moving target with a RWS mounted on TAPV platform. With these scenarios and a step-to-step procedure, the overall budget error can be completely filled. With the complete budget error, the weapon system will be characterized and the numerical simulation will be available to extrapolate its performance for various operating conditions.

3.2.1 Static-Static scenario (step 1)

The static-static scenario is the case where a static vehicle engages a static target (Figure 3). This scenario is the simplest system and gives the possibility to fill the gun laying dispersion (S_{GLD}) shown in the budget error. However, section 3.1.5.1 presents another methodology to obtain the gun laying dispersion. In this case, this static-static scenario can be used to update or validate one parameter if the analyst feels less confident in his assumption. Nonetheless, this static-static scenario will be used only to obtain the gun laying dispersion.

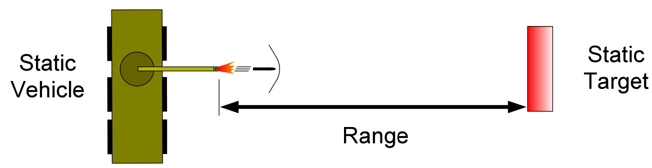

Figure 3: Representation of a possible static-static scenario.

This following analysis assumes that some data (error source) of the static-static scenario are available from the experimental trials (for example) to fill part of the budget error such as: S_{Total}, S_{GD}, S_{WD} and S_{PD}. For this simplest engagement scenario, the fire control system dispersion can be simplified to the gun laying dispersion, because the target's tracking, vehicle movement and mutual interaction dispersion becomes null without the vehicle and/or target movement, equation (27):

$$S_{FCS} = \sqrt{S_{GLD}^2 + \underbrace{S_{TTD}^2}_{0} + \underbrace{S_{VMD}^2}_{0} + \underbrace{S_{MID}^2}_{0}} = S_{GLD} \tag{27}$$

In this case, the gun laying dispersion is obtained by the resolution of equation (28).

$$S_{GLD} = S_{FCS} = \sqrt{S_{Total}^2 - S_{PD}^2 - S_{GD}^2 - S_{WD}^2} \tag{28}$$

3.2.2 Static- Moving scenario (step 2)

The static-moving scenario is the case where the vehicle is static and engages a moving target (Figure 4). This scenario is the second step procedure and gives the possibility to fill the target's tracking dispersion (S_{TTD}) shown in the budget error. The target's tracking dispersion can also be obtained experimentally, but the methodology to evaluate the standard deviation in the average relative target velocity becomes a difficult process (Shown in section 3.1.5.2). However, the budget error analysis gives the simplest methodology to approximate the target's tracking effect.

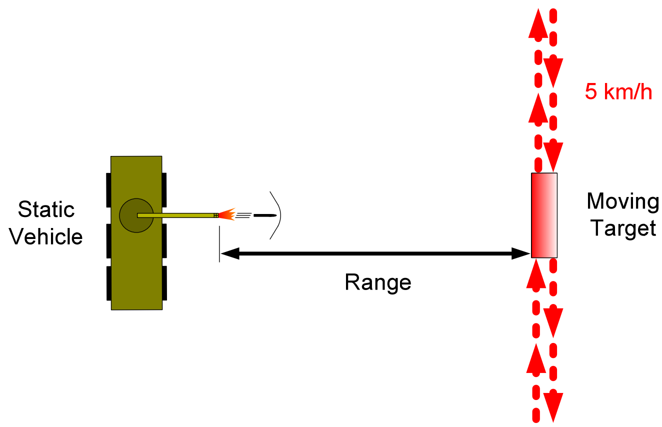

Figure 4: Representation of a possible static vehicle and moving target engagement.

This following analysis assumes that some data (error source) of the static-moving scenario are available from the experimental trials (for example) to fill part of the budget error such as: S_{Total}, S_{GD}, S_{WD} and S_{PD}. Also, the analysis takes into account the value obtained for the gun laying dispersion (S_{GLD}) from the static-static scenario (Step 1). For the second scenario, the target's tracking dispersion can be easily extracted from the fire control system dispersion, because the vehicle movement and the mutual interaction dispersion becomes null without the vehicle movement, equations (29) and (30):

$$S_{FCS} = \sqrt{S_{GLD}^2 + S_{TTD}^2 + \underbrace{S_{VMD}^2}_{0} + \underbrace{S_{TMD}^2}_{0}} \tag{29}$$

$$S_{TTD} = \sqrt{S_{FCS}^2 - S_{GLD}^2} \tag{30}$$

In this case, the target's tracking dispersion is obtained by the resolution of equation (31).

$$S_{TTD} = \sqrt{S_{Total}^2 - S_{PD}^2 - S_{GD}^2 - S_{WD}^2 - S_{GLD}^2} \tag{31}$$

3.2.3 Moving-Static scenario (step 3)

The moving-static scenario is the case where the moving vehicle engages a static target (Figure 5). This scenario is the third step procedure and gives the possibility to fill the vehicle movement dispersion (S_{VMD}) shown in the budget error. The vehicle movement dispersion can also be obtained experimentally, but the methodology will require a specific resource, such as the vehicle dynamic respond test rig. The experimental methodology will be an offline firing analysis. However, the budget error analysis gives the simplest methodology to approximate the vehicle movement effect.

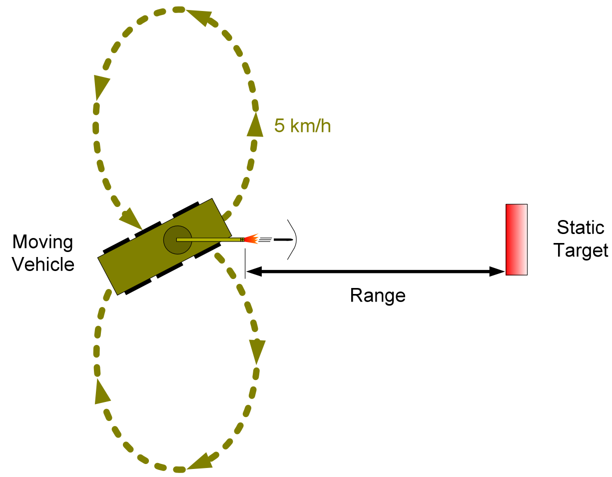

Figure 5: Representation of a possible moving vehicle and static target engagement.

This following analysis assumes that some data (error source) of the moving-static scenario are available from the experimental trials (for example) to fill part of the budget error such as: S_{Total}, S_{GD}, S_{WD} and S_{PD}. Also, the analysis takes into account the value obtained for the gun laying (S_{GLD}) and target's tracking (S_{TTD}) dispersion from previous scenarios (Step 1 and 2). For the third scenario, the vehicle movement dispersion can be easily extracted from the fire control system dispersion, because the mutual interaction dispersion becomes null without the target movement, equations (32) and (33):

$$S_{FCS} = \sqrt{S_{GLD}^2 + S_{TTD}^2 + S_{VMD}^2 + \underbrace{S_{TMD}^2}_{0}} \tag{32}$$

$$S_{VMD} = \sqrt{S_{FCS}^2 - S_{GLD}^2 - S_{TTD}^2} \tag{33}$$

In this case, the vehicle movement dispersion is obtained by the resolution of equation (34).

$$S_{VMD} = \sqrt{S_{Total}^2 - S_{PD}^2 - S_{GD}^2 - S_{WD}^2 - S_{GLD}^2 - S_{TTD}^2} \tag{34}$$

3.2.4 Moving- Moving scenario (step 4)

The moving-moving scenario is the case where the moving vehicle engages a moving target (Figure 6). This scenario is the last step procedure and gives the possibility to fill the mutual interaction dispersion (S_{MID}) shown in the budget error. The vehicle mutual interaction can also be obtained experimentally, but the methodology will be a difficult process. However, the budget error analysis gives the simplest methodology to approximate the mutual interaction effect.

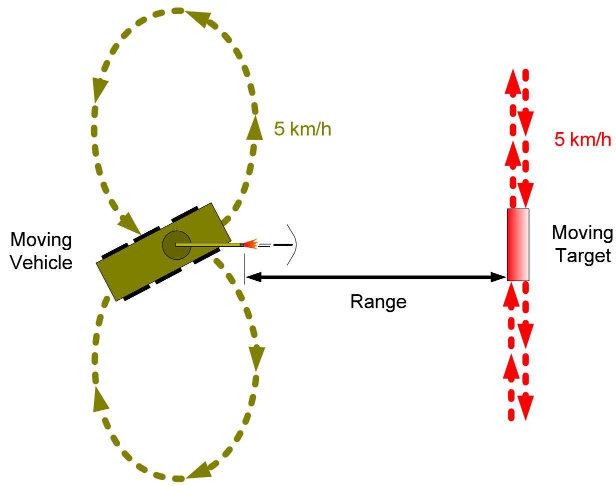

Figure 6: Representation of a possible moving vehicle and moving target engagement.

This following analysis assumes that some data (error source) of the moving-moving scenario are available from the experimental trials (for example) to fill a part of the budget error such as: S_{Total}, S_{GD}, S_{WD} and S_{PD}. Also, the analysis takes into account the value obtained for the gun laying (S_{GLD}), target's tracking (S_{TTD}) and vehicle movement (S_{VMD}) dispersion from the previous scenarios (Steps 1, 2 and 3). For the last scenario, the mutual interaction dispersion can be easily extracted from the fire control system dispersion, equations (35) and (36):

$$S_{FCS} = \sqrt{S_{GLD}^2 + S_{TTD}^2 + S_{VMD}^2 + S_{MID}^2} \tag{35}$$

$$S_{MID} = \sqrt{S_{FCS}^2 - S_{GLD}^2 - S_{TTD}^2 - S_{VMD}^2} \tag{36}$$

In this case, the vehicle movement dispersion is obtained by the resolution of equation (37).

$$S_{MID} = \sqrt{S_{Total}^2 - S_{PD}^2 - S_{GD}^2 - S_{WD}^2 - S_{GLD}^2 - S_{TTD}^2 - S_{VMD}^2} \tag{37}$$

3.3 PRODAS simulation package

To provide an ammunition PHit simulation of the C6 GPMG and 40 mm AGL weapons integrated on a RWS mounted on a typical TAPV, the PRODAS© (**PRO**jectile **D**esign/**A**nalysis **S**ystem) [5] software package, version 3.5.3 with the Ground-to-Ground System Effectiveness Simulation module version 4.1.0, will be used to accomplish this work. This section provides a brief summary of the PRODAS Simulation Package. The software was developed to satisfy a need for a rapid performance evaluation of ammunition characteristics.

Projectile design and performance evaluation, in general, requires a detailed analysis and testing involving interior, exterior, and terminal ballistics. The design process can be formulated in many ways depending on the information available concerning the target, weapon system and application. The ammunition performance characteristics resulting from the design process plays an important role in defining other components of the weapon system.

The basic projectile design analysis considerations that must be addressed are briefly stated as followed but are not limited to:

Ammunition Type:	7.62 mm C19 tracer 7.62 mm C21 ball 40 mm Target Practice (TP) 40 mm High Explosive (HE) 40 mm High Explosive Dual Purpose (HEDP) 40 mm Air Bursting Ammunition (ABM)

Physical Constraints - Geometric and Physical Properties

Exterior Ballistics:	Spin-Fin-Rare Stabilized Aerodynamics Stability Time of Flight Velocity Accuracy – Dispersion Tracer
Interior Ballistics:	Impulse Chamber Pressure Velocity – Acceleration Propellant Primer Rotating Band

Structural Integrity:	Setback Torque Deflections Balloting
Terminal Ballistics:	Target Penetration HE / Fragmentation Effectiveness Ewing Lethality
System Analysis:	Engagement Scenarios Atmospheric Errors Fire Control Error Aiming Errors Single Shot vs. Bursts Projectile Accuracy/Dispersion

These design/analysis considerations are not all inclusive. They illustrate the diversity of the analyses required, and the need for trade-off analyses and iterative procedures, to arrive at the optimum projectile or rocket design. It is obvious, due to the coupled nature of the analyses required, that a unified analytical approach would have a significant effect on the design and performance evaluation cycle time.

The development of an effective design/analysis tool for use by the design engineer in the development and evaluation of projectiles has been a multi-year project, which began at General Electric in 1972 and has continued at Arrow Tech Associates, Inc. since 1991. The developed tool is called PRODAS, which is an acronym for the Projectile Design/Analysis System.

The primary objective of the PRODAS development has been to provide an effective analytical tool that allows for rapid and complete design of projectiles and rockets. In general, the system makes use of the display and interaction capabilities of interactive graphics to provide the engineer with a user-friendly working environment. The basic approach has been to develop PRODAS in an open-ended fashion, such that, as its capabilities are extended, it always exists as a functional design analysis tool. The projectile modeling phase and interactive graphics medium provide the design capability. The analysis capability is provided by the methodology and techniques contained in the individual analysis segments.

PRODAS has been developed using proven methodologies and techniques such that predicted performance estimates are based in part on prior experimental testing. The approach has been to link these diversified analyses together by means of a common database such that the required results of one analysis feeds directly to the subsequent analysis. For example, the stability analysis results in the estimation of the aerodynamic force and moment coefficients. These are passed directly to the trajectory analysis for input towards evaluating the motion patterns that may result during the actual firings. The common database provides inherent continuity. Utilizing the interactive graphics medium provides effective presentation of the results for rapid interpretation by the engineer and subsequent iteration with modified input conditions. The database is maintained such that, as experimental data becomes available, the analysis may be easily redone using the actual parameters instead of estimated parameters.

Program input/output at the users option, can be either Metric or English. The PRODAS analysis options are outlined in the following diagram.

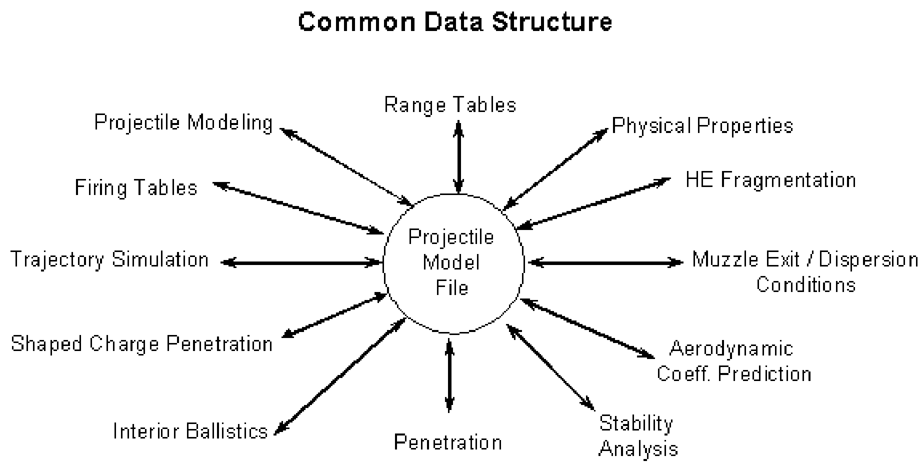

Figure 7: PRODAS analysis options.

3.3.1 Inputs to PRODAS module

In the following sections, each individual module that will be used and required in the system analysis study will be briefly explained and inputs required will be stated.

3.3.1.1 Geometry and mass module

Computation of the weight, axial and transverse inertia and center of gravity location for each components, sub-assemblies and total assembly, as well as for several pre-defined assemblies, is done in this module.

The aforementioned parameters are actually computed on an element-by-element basis. The element results are summed to compute values for the higher-level entities. An element with a radius (concave or convex) is automatically broken down into fifty (50) frustums; computations are done for each frustum and the results appropriately summed. The centers of gravity computed for components, sub-assemblies, and the total assembly are referenced from the reference location of the component or sub-assembly, whereas the centers of gravity for the pre-defined sub-assemblies are referenced from the nose of the sub-assembly. Pre-defined sub-assemblies include:

- Total Projectile (all components in the model)
- Launch Vehicle (excludes propellant and cartridge case, if modeled)
- Flight Vehicle (further excludes discarded components, such as sabot)
- Flight Vehicle after burnout (further excludes tracer material)
- Projectile Carrier (includes only discarding components, such as sabot)

Figure 8 shows an example of the geometry model needed and Table 15 gives a summary of the projectile's properties required to run correctly the PRODAS model.

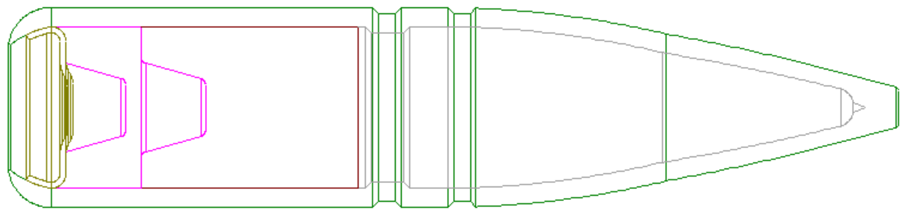

Figure 8: Projectile geometry example - 7.62 mm C19.

Table 15: Ammunition mass model properties.

Symbol	**Description**
d	Reference diameter (mm)
l	Reference length (mm)
m	Reference mass (g)
I_X	Axial moment of inertia (g.cm2)
I_Y	Transverse moment of inertia about center of gravity (g.cm2)
X_{CG}	Center of gravity from nose (mm)

3.3.1.2 The aero predictions module

The Aero Prediction module predicts the aerodynamic coefficient and stability derivatives that are necessary to conduct stability analysis, trajectory computations, generate firing tables and perform other analyses. The aerodynamic coefficients that are necessary are also defined in NATO STANAG 4355 [6] and NATO STANAG 4144 [7]. Table 16 shows an example of the aerodynamic coefficients and stability derivatives required to run correctly the PRODAS model.

Table 16: Example of the aerodynamic coefficients and stability derivatives.

Mach	Cx_o	Cx_2	CN_α	Cm_α	Cm_q	Cl_p	Cnp_α
0.01	0.25	2.29	1.85	2.18	-5.20	-0.02	-1.63
0.40	0.25	2.29	1.85	2.15	-5.20	-0.02	-1.63
0.60	0.25	2.29	1.85	2.13	-5.20	-0.02	-1.63
0.70	0.25	2.54	1.85	2.13	-5.20	-0.02	-1.75
0.75	0.25	2.64	1.85	2.13	-5.40	-0.02	-1.70
0.80	0.25	2.73	1.90	2.20	-5.60	-0.02	-1.53
0.85	0.25	2.85	1.93	2.22	-6.00	-0.02	-1.20
0.88	0.22	2.96	1.97	2.27	-6.50	-0.02	-1.00
0.90	0.20	3.07	2.01	2.34	-7.20	-0.02	-0.98
0.93	0.22	3.23	2.07	2.45	-8.10	-0.02	-0.84
0.95	0.25	3.41	2.13	2.54	-9.20	-0.02	-0.59
0.98	0.27	3.61	2.17	2.55	-10.10	-0.02	-0.31
1.00	0.33	3.85	2.19	2.49	-11.10	-0.02	-0.18
1.03	0.36	4.09	2.19	2.42	-12.30	-0.02	0.04
1.05	0.40	4.35	2.20	2.37	-13.40	-0.02	0.13
1.10	0.39	4.81	2.26	2.34	-15.30	-0.02	0.25
1.20	0.37	5.21	2.37	2.35	-17.20	-0.02	0.29
1.35	0.36	4.63	2.49	2.30	-17.60	-0.02	0.35
1.50	0.34	4.09	2.60	2.05	-17.20	-0.02	0.44
1.75	0.32	3.55	2.73	1.82	-16.60	-0.02	0.42
2.00	0.31	2.97	2.82	1.70	-15.90	-0.01	0.42
2.25	0.30	2.68	2.88	1.58	-15.50	-0.01	0.41
2.50	0.29	2.41	2.89	1.51	-15.20	-0.01	0.41
3.00	0.28	1.94	2.87	1.43	-14.20	-0.01	0.40
3.50	0.27	1.72	2.76	1.42	-12.80	-0.01	0.40
4.00	0.26	1.55	2.69	1.50	-12.10	-0.01	0.40
4.50	0.25	1.36	2.64	1.54	-11.40	-0.01	0.40
5.00	0.24	1.18	2.60	1.57	-10.80	-0.01	0.40

3.3.1.3 **Exit muzzle module**

In the case where the ammunition does not have experimental data on the ammunition dispersion, the budget error will use the theoretical model. The Muzzle Exit segment of PRODAS computes the dispersion (jump) of projectiles due to in-bore yaw and induced yaw rate. The theoretical closed form jump equation shown in this section includes the projectile aerodynamic/physical properties and the projectile to gun bore clearance. This segment will consider only the initial muzzle exit yaw angle and muzzle exit yaw rate components of the total jump. Dispersion is defined as the standard deviation of the projectile impact about the MPI. The ammunition dispersion ($\mathrm{A_D}$) can be approximated by the combined effects of the aerodynamic ($\mathrm{AJ_D}$) and projectile ($\mathrm{PJ_D}$) jump as shown in equation (38):

$$\mathrm{A_D} = \sqrt{\mathrm{AJ_D^2} + \mathrm{PJ_D^2}} \tag{38}$$

The aerodynamic jump can be obtained and approximated by the linear theory of ballistics, where δ_b is the projectile in-bore yaw, and V_0 is the muzzle velocity as shown in equation (39):

$$\mathrm{AJ_D} = \frac{(C_{N\alpha} - C_X)}{C_{m\alpha}} \frac{(I_Y - I_X)}{md^2} \frac{d}{V_0} (\delta_b p) \tag{39}$$

The projectile in-bore yaw can be approximated from the difference between the barrel diameter (d_b) and the projectile diameter (d) divided by the bourrelet/wheelbase length (l_b) as shown in equation (40):

$$\delta_b = \frac{d_b - d}{l_b} \tag{40}$$

The projectile jump is the effect of the center of gravity, where CG_{off} is the offset from a projectile x-axis as shown in equation (41):

$$\mathrm{PJ_D} = \frac{p\ CG_{off}}{V_0} \tag{41}$$

3.3.1.4 **Thrust/Tracer/Base burn module**

In the case where the ammunition has a tracer capability, the Thrust/Tracer/Base Burn segment of PRODAS computes the thrust, tracer and/or base effect during the trajectory analysis. The model requires the thrust or drag variation data versus time.

3.3.1.5 **Ground-to-Ground module**

The Ground-to-Ground System Effectiveness Simulation is a state-of-the-art computer tool designed to facilitate tradeoffs between candidate ammunition and gun system, burst length, targets, sensor errors and system accuracy. This program is focused on the effectiveness in hitting and killing the intended target.

The simulation brings together the models for the gun, ammunition, fire control system and target into a simultaneous simulation. First the probability of hit is calculated and then the kill assessment is established based on the user input target vulnerability.

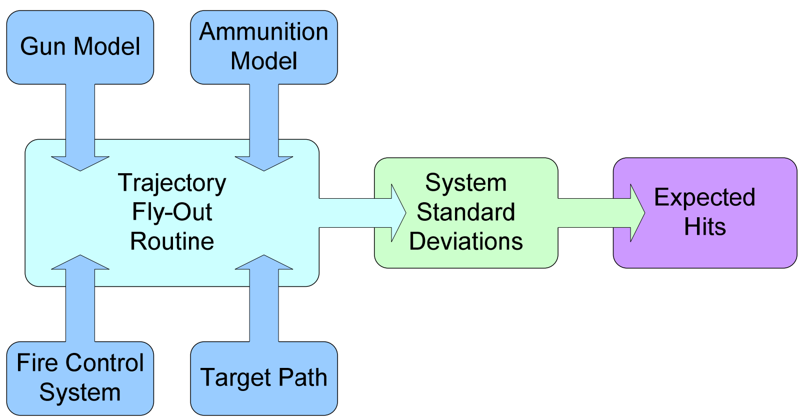

Figure 9: System effectiveness simulation block diagram.

The fragment hit probability and lethality shall be conducted with other computer simulation tools such as GVAM. Separate classified reports will be published to investigate the terminal aspects, i.e., the lethality studies, based on the outputs of the Ground-to-Ground System Effectiveness Simulations.

The Ground-to-Ground system effectiveness analysis consists of a Monte Carlo methodology with various system errors as inputs to provide standard deviations in range, cross range and height at specified ranges.

The inputs to this module basically consist of an error budget that will characterize the gun-ammunition combination. It assumes that corrections for biases have been done, as for example: constant wind (head/tail), non-standard atmospheric conditions, change of muzzle velocities due to propellant temperature, etc... It assumes that the aim point of the intended target will be at the

center of the target and that system errors will be added on. Due to this, the trajectory flyout routine consists of a 2DOF.

Various attack scenarios can be modeled:

- Direct attack impact fuze against vertical target. This mode is used for validating the probability of hit against side profile vehicle targets.

- Top attack (Material) impact fuze against a horizontal target with direct (low QE) and indirect (high QE) fire options. This mode is used for va1idating the “heating zone” requirement.

- Top attack (troops) impact or airburst fuze against a number of troops in a given area with direct (low QE) and indirect (high QE) fire options. This mode will be used for the validation of airburst requirements.

A typical input error file for this module is provided in Table 17. As seen in the table, the errors are classified as occasion-to-occasion and round-to-round. All the errors either contribute in the azimuth plane (drift) or in the elevation plane (range). When firing in burst mode, only the errors in the round-to-round columns are acted upon.

Table 17: Typical inputs file for system effectiveness simulation (fictive values).

```
                   System Errors
                     Occ To Occ          Rnd To Rnd
Categories  Units     El     Az           El     Az
                     Rng    Drf          Rng    Drf
----------------------------------------------------
 FC Range  m         2.50
 FC Range  %         0.00
 Tar Vel   m/s              0.00
 Boresight mils      2.45   3.12
 Gun Aim   mils      3.10   5.20
 Cant      deg              2.40
 Gun Disp  mils                          0.64   1.20
 Ammo Disp mils                          1.20   1.20

 Muz Vel   m/s       2.00                3.40
 Drag/Mass %                             2.20
 Thrust    %                             1.00
 Winds     m/s       1.30   1.30
 Temp      DegC      0.50
 Pressure  mbar      2.00
```

Each individual error from Table 17 is described below. However, the required inputs of the Ground-to-Ground System Effectiveness Simulation are slightly different of the methodology developed in sections 3.1 and 3.2. Thus, each individual description would be described in the implementation of the methodology parameter.

1. **FC Range (m or %):** This is the error in determining the range to the target from the firing position, in terms of meter or percentage of the range. It is mainly composed (if

direct firing) of the Laser Range Finder accuracy. The model allows that the range error be entered as either a fixed distance value (previous error) or a percentage (linear value). It should be noted that the accuracy of the LRF could be affected by the target type and shape. Therefore, various simulations should be conducted for anti-personnel and anti-vehicle scenarios. In sections 3.1 and 3.2, this error is the standard deviation of the error of the target range ($R_{\text{Target}}^{\text{SD}}$).

2. **Tar Vel (m/s):** This is the error due to the target velocity (if applicable). This input is one of the inputs that will be used to simulate the target's tracking error of section 3.1.5.2. In sections 3.1 and 3.2, this error is the standard deviation in the average relative target velocity (V_{Target}^{SD}) and the evaluation of this parameter has been evaluated by equation (25) and by the analysis of the experimental data.

3. **Boresight (mils):** The Boresight error is an alignment error, which is composed of all the errors that are attributed to the fire control system/display. It can be different in azimuth and in elevation. In sections 3.1 and 3.2, this error is the standard deviation of the gun laying ($\mathrm{S}_{\mathrm{GLD}}$) and the evaluation of this parameter is done by equation (24).

4. **Gun Aim (mils):** The aiming error is composed of all errors from the mechanical aiming of the gun that is not related to the fire control system. It can be different in azimuth and in elevation. In sections 3.1 and 3.2, this error is the root of the square summation the two (2) different dispersion subsections such as: vehicle movement and mutual interaction. Equation (42) shows this relation and the evaluation of this parameter has been done by the analysis of the experimental data.

$$\text{Aiming Error } = \sqrt{\mathrm{S}_{\mathrm{VMD}}^2 + \mathrm{S}_{\mathrm{MID}}^2} \qquad (42)$$

5. **Cant (deg):** This is the cant angle error of the gun in the azimuth plane. It is mainly composed (if measured) of the cant sensor value. This input is one of the inputs that will be used to simulate the target's tracking error of section 3.1.5.2. In sections 3.1 and 3.2, this error is the cant angle of gun mounts in the azimuth plane ($\theta_{\text{Gun}}^{\text{Erro}}$).

6. **Gun Disp (mils):** The Gun Dispersion error is the error of the overall gun dispersion (Gun Support and Gun Barrel Dispersion). This error is a round-to-round error. It can be different in azimuth and in elevation. In sections 3.1 and 3.2, this error is the standard deviation of the overall gun dispersion (S_{GD}) and the evaluation of this parameter has been done by the experimental data analysis.

7. **Ammo Disp (mils):** The Ammunition dispersion error, as measured through Projectile Jump testing in an aeroballistics range trial. This error is a round-to-round error. In sections 3.1 and 3.2, this error is also the standard deviation of Ammunition Dispersion (S_{AD}) and the evaluation of this parameter can't be used for the theoretical analysis (section 3.3.1.3) or the experimental aeroballistics range data.

8. **Muz Vel (m/s):** This is the Muzzle Velocity error, between lots (Occasion-to-occasion) and within a Lot (Round-to-round). In sections 3.1 and 3.2, this error is also the Muzzle Velocity error where V_M^{SD-LL} is for occasion-to-occasion and V_M^{SD-RR} is for round-to-round. The evaluation of this parameter has been done usually with the experimental Doppler radar data.

9. **Drag/Mass (%):** This is the ammunition mass and drag error. The ammunition mass error is the round-to-round mass tolerance over an ammunition lot. The Drag error is the variation of the drag coefficient (or the retard) over the trajectory (from the shape reproduction/tolerance, rotating band ware, etc). This error affects the velocity of the projectile as the projectile flies downrange. It is provided as a percentage over the mean and the standard deviation of measured values. In sections 3.1 and 3.2, this error is also the standard deviation of Drag/Mass percentage ratio ($D/M_{\%}^{SD}$). The evaluation of this parameter is done by equation (16) and by the experimental Doppler radar and mass data.

10. **Thrust (%):** This is the ammunition tracer error (if applicable). The ammunition tracer error is the round-to-round delta drag variation over an ammunition lot. In sections 3.1 and 3.2, this error is also the standard deviation of the tracer ($Tr_{\%}^{SD}$). The evaluation of this parameter is obtained by equation (21) and by the experimental aeroballistics range data.

11. **Winds (m/s):** This is the error in the average wind speed. In sections 3.1 and 3.2, this error is also the standard deviation of the error of the average wind speed along the trajectory (V_W^{SD}). Experimentally, the error due to the average wind speed is calculated simultaneously along the projectile path from two (2) (or more) meteorological stations.

12. **Temp (^{o}C):** This is the temperature error at gun site. It is mainly composed (if measured) of the temperature sensor accuracy. In sections 3.1 and 3.2, this error is also the standard deviation of the error on the atmospheric temperature at gun site (T_A^{SD}). Experimentally, the temperature error is calculated simultaneously along the projectile path from two (2) (or more) meteorological stations.

13. **Pressure (mbar):** This is the atmospheric pressure error at gun site. It is mainly composed (if measured) of the pressure sensor accuracy. In sections 3.1 and 3.2, this error is also the standard deviation of the error on the atmospheric pressure at gun site (P_A^{SD}). Experimentally, the pressure error is calculated simultaneously along the projectile path from two (2) (or more) meteorological stations.

14. **Time fu ze (%):** This is time fuze error for the airburst ammunition, in terms of percentage of time flight.

4 Probability of hit formulation

The RFP for the TAPV acquisition project requires providing recommendations for the following, considering that the weapons are integrated on an RWS mounted on typical TAPV:

- Threshold and rated PHit data for the CF in service C6 GPMG weapons;
- Threshold and rated PHit data for the CASW 40 mm AGL High Explosive Dual Purpose – Self Destruct (HEDP-SD) ammunition on vehicle and infantry targets;
- Threshold and rated PHit data for the CASW 40 mm AGL Practice Rounds (Target Practice and Target Practice with Tracer);
- Threshold and rated PHit data for the CASW 40 mm AGL Airburst Ammunition (ABM) round on infantry targets;

Studies shall be conducted to evaluate the various parameters for a multitude of firing scenarios from various data sources such as: theoretical analysis, references and/or experimental data.

Monte Carlo simulations shall be conducted at various ranges and on various targets based on the above errors to obtain expected hits on personal and vehicle targets in a direct hit scenario. These errors are then added from standard initial conditions obtained from the firing table.

The PRODAS Ground-to-Ground simulation tool can provide the average and the standard deviations in range, cross range and height at specified ranges with a PRODAS error budget (Table 18). The expected probabilities of hits are then calculated based on a target size and firing scenarios.

The PRODAS simulation tool can also compute the above for a burst of N shots. For our particular cases, a group of N shots in a burst will be considered as one shot since the dispersions for a group of 3, 5 and more hot burst will be known and treated as independent shots.

For a direct attack scenario against a vertical target, the average standard deviations in the vertical and horizontal directions are calculated for specified ranges.

Table 18: PRODAS error budget.

Symbol	Unit	Description
$Tr_{\%}^{SD}$	%	Standard Deviation of the tracer
$D/M_{\%}^{SD}$	%	Standard Deviation of Drag Mass percentage ratio
V_{M}^{SD-RR}	m/s	Standard Deviation of muzzle velocity within a lot of ammunition at 21 °C
V_{M}^{SD-LL}	m/s	Standard Deviation of muzzle velocity between lots of ammunition at 21 °C
A_{D}	mils	Standard Deviation of the Ammunition Dispersion.
GS_{D}^{SD}	mils	Standard Deviation of the Gun Support Dispersion
G_{D}^{SD}	mils	Standard Deviation of the Gun Barrel Dispersion
V_{W}^{SD}	m/s	Standard Deviation of the error of the average wind speed along the trajectory
P_{A}^{SD}	mbar	Standard Deviation of the error on the atmospheric pressure at gun site
T_{A}^{SD}	°C	Standard Deviation of the error on the atmospheric temperature at gun site
S_{GLD}	mils	Standard Deviation of the Gun Laying Dispersion
R_{Target}^{SD}	m	Standard Deviation of the error of the target range.
θ_{Gun}^{Error}	deg	Cant angle of gun mounts in the azimuth plane
V_{Target}^{SD}	meter/s	Standard Deviation in the average relative target velocity.
S_{VMD}	mils	Standard Deviation of the Vehicle Movement Dispersion
S_{MID}	mils	Standard Deviation of Mutual Interaction Dispersion

4.1 Target standard

To provide a threshold and rated PHit, the knowledge of the target dimensions is important. The probability of hit can depend largely on the target height and width. In this case, the present section shows the distinction between the personal and vehicle target.

4.1.1 Personal target

The dismounted personal target dimensions that are necessary to conduct to the threshold and rated Probability of Hit for a specific weapon are defined in NATO STANAG 4512 [8]. However, Project Management Office (PMO) Tactical Armoured Patrol Vehicle (TAPV) recommends using a simplified rectangular target form. The dismounted personal target dimensions will be 1.5 m (height) by 0.6 m (width).

4.1.2 Vehicle target

The vehicle target dimensions that are necessary to conduct to the threshold and rated PHit for a specific weapon are defined in NATO STANAG 4512 [9]. However, Project Management Office (PMO) Tactical Armoured Patrol Vehicle (TAPV) recommends using a simplified rectangular target form. The vehicle target dimensions will be 2.3 m (height) by 2.3 m (width).

4.2 Formulation

For a specified target size, the PRODAS Ground-to-Ground simulation module calculates the expected hits for a direct and top attack scenario. The expected probability of at least one hit over N shots is given by equation (43):

$$P^*_{Hit} = 1 - \left(1 - \frac{E}{M}\right)^N \tag{43}$$

N - Number of rounds in a burst
E - Expected number of hits for M rounds (From the PRODAS Monte Carlo simulations)
M - Number of rounds fired for Monte-Carlo Method (predefined in PRODAS)

If N = 1; $P^*_{Hit} = \frac{E}{M}$, i.e. the expected probability of hit for one shot. This is the value obtained from PRODAS Monte Carlo simulations.

Equation (43) can be reformulated as followed to obtain the required $\frac{E}{M}$ for a given P^*_{Hit} and N number of shots in a burst, equation (44):

$$\frac{E}{M} = P^{1S}_{Hit} = 1 - e^{\frac{\ln\left(1 - P^*_{Hit}\right)}{N}} = 1 - \left(1 - P^*_{Hit}\right)^{1/N} \tag{44}$$

or to obtain the number of shots required to achieve a probability of at least one hit, equation (45):

$$N = \frac{\ln\left(1 - P^*_{Hit}\right)}{\ln\left(1 - P^{1S}_{Hit}\right)} \tag{45}$$

5 Comments and Conclusions

A PHit methodology has been developed to characterize the overall performance of the C6 GPMG and 40 mm AGL integrated on RWS mounted on TAPV Platform. The methodology takes into account four (4) different scenarios (static/moving vehicle to engage the static/moving target) into an error budget.

The error budget analysis breaks down the total dispersion (standard deviation of the impact point position) into four (4) main error sources: weather, gun, projectile and FCS dispersion. The weather dispersion can be developed to see the individual contributions of the standard deviation of the wind speed, atmospheric temperature and atmospheric pressure. The Gun dispersion can be developed to see the individual contributions of the standard deviation of the gun support play and the gun barrel. The projectile dispersion can be developed to see the individual contributions of the standard deviation of the ammunition dispersion, muzzle velocity, drag mass ratio and tracer effect. The fire control system dispersion can be developed to see the individual contributions of the standard deviation of the gun laying, target's tracking, vehicle movement and mutual interaction effect.

To fill the error budget, each error source and the relation between them were described in the experimental and theoretical point view (if applicable). Also, by resolving the error budget, it's now possible to easily extract the fire control system, gun laying, target's tracking, vehicle movement and mutual interaction dispersion.

The error budget can be represented on a pie plot in square mils (mils^2), because each error source has the same unit (mils). The error budget can be also represented on a stacked area plot in square mils (mils^2) for different target range and/or different parametric studies.

To create the error budget, the PRODAS budget error was built to describe the required inputs for the system simulation (PRODAS). The methodology to fill the PRODAS budget error was also presented. With the PRODAS budget error and simulation package, the numerical simulation can be easily used to obtain the weapon system performance for different firings conditions.

Experimental data is required to refine the numerical simulation on the TAPV RWS system. The main difficulties are to characterise the target's tracking, vehicle movement and mutual interaction effect. These effects need to take into account the vehicle, gunner and RWS interaction effect on the weapon accuracy. Also, the RWS doesn't have a wind speed and direction sensor to take into account the weather effect on the accuracy. In addition, the driver and gunner experience can have a large influence on the overall system weapon. All these effects need to be approximated to be able to characterize the realistic weapon performance.

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[7] NATO STANAG 4144 – "Procedure to Determine the Fire Control Inputs to use in indirect Fire control System", Edition 2, 2002.

[8] NATO STANAG 4512 – "Dismounted Personal Target", Edition 1, 1995.

[9] NATO STANAG 4498 – "Unarmoured Vehicle, Helicopters and flied fortification targets", Edition 1, 2004.

List of symbols/abbreviations/acronyms/initialisms

A_{ref}	projectile reference area, m^2
AJ_D	Standard deviation of the Aerodynamic jump, mils
B_{SOL}^{SD}	Ballistic FCS solution error
C_{X0}^{AT}	Tracer coefficient of the projectile with the active tracer effect
C_{X0}^{WT}	Tracer coefficient of the projectile without the tracer effect
C_{X0}, Cx_o	Drag coefficient of the projectile (Axial force coefficient)
$\overline{C_{X0}}$	Average of the drag coefficient of the projectile
C_{X0}^{SD}	SD of the drag coefficient of the projectile
$C_{X0_{\%}}^{SD}$	Percentage of the SD of the drag coefficient of the projectile
Cx_2	Square-yaw axial force coefficient
CG_{off}	Center of gravity offset from a projectile x-axis, m
Cl_p	Roll damping moment coefficient
Cm_α	Pitching moment coefficient
Cm_q	Pitch damping moment coefficient
CN_α	Normal force coefficient
Cnp_α	Magnus moment coefficient
d	Projectile reference diameter, m
$D_{M/RWS}$	Distance between the RWS rotation axis and the barrel muzzle exit, m
D_R^{SD}	Display resolution error, mrad
$D/M_{\%}^{SD}$	SD of Drag Mass percentage ratio, %
E	Expected number of hits for M rounds
$\overline{H_{Target}}$	Average target base altitude, m
H_{Target}^{SD}	Standard Deviation of the error in knowing the target base altitude, m
I_X	Axial moment of inertia, g cm^2
I_Y	Transverse moment of inertia about center of gravity, g cm^2
l	Reference length, m
l_b	bourrelet/wheelbase length, m
LOS^{SD}	Line of sight stability error, mrad
m, M	Projectile mass, kg
$\overline{M}$	Average of the mass of projectile, kg
M^{SD}	SD of the mass of projectile, kg

$M_{\%}^{SD}$	Percentage of the SD of the mass of projectile, %
M_{A}^{SD}	Misalignment error of FCS with gun, mrad
$M_{P}(t)$	tracer powder mass as function of time, kg
Mach	Mach Number
N	Number of round
ND_{R}^{SD}	Night/day resolution error, mrad
p	is the spin rate, rad/s
P_{A}^{SD}	Std. deviation of the error on the atmospheric pressure at gun site, mbar
PJ_{D}	Standard deviation of the Projectile jump, mils
P_{Hit}^{*}	Probability of at least one hit over N shots
P_{Hit}^{1S}	Probability of hit for one shot
$\overline{R_{Target}}$	Average target range, m
R_{Target}^{SD}	Standard Deviation of the error of the target range, m
S_{AD}, A_{D}	Ammunition Dispersion, mils
$S_{D/M}$	Drag/Mass Dispersion, mils
S_{FCS}	Fire Control System Dispersion, mils
S_{GB}	Gun Barrel Dispersion, mils
S_{GD}	Gun Dispersion, mils
S_{GLD}	Standard Deviation of the Gun Laying Dispersion, mils
S_{GSP}	Gun Support Play Dispersion, mils
S_{MID}	Mutual Interaction Dispersion, mils
S_{P_A}	Atmospheric pressure dispersion, mils
S_{PD}	Projectile Dispersion, mils
S_{T_A}	Atmospheric temperature dispersion, mils
S_{TD}	Tracer Dispersion, mils
S_{TTD}	Standard Deviation Target's Tracking Dispersion, mils
S_{Total}	Global dispersion, mils
$S_{V_{MV}}$	Muzzle Velocity Dispersion, mils
S_{V_W}	Wing speed dispersion, mils
S_{VMD}	Vehicle Movement Dispersion, mils
S_{WD}	Weather dispersion, mils
SD, σ	Standard deviation
T_{A}^{SD}	Std. deviation of the error on the atmospheric temperature at gun site, °C

Tr	Thrust/tracer coefficient of the projectile
$\overline{\mathrm{Tr}}$	Average of the thrust/tracer coefficient of projectile
Tr^{SD}	SD of the tracer
$\mathrm{Tr}_{\%}^{SD}$	Percentage of SD of the tracer, %
V	Projectile velocity
V_M	Muzzle velocity at 21 °C, m/s
V_M^{SD-RR}	SD of muzzle velocity within a lot of ammunition at 21 °C, m/s
V_M^{SD-LL}	SD of muzzle velocity between lots of ammunition at 21 °C, m/s
V_{Target}^{SD}	Standard Deviation in the average relative target velocity, m/s
V_W^{SD}	Standard deviation of the error of the average wind speed along the trajectory, m/s
X_{CG}	Center of gravity from nose, m
X_{GD}^{SD}	Standard deviation of the overall gun barrel head position, m
X_{GL}^{SD}	Standard Deviation of the gun laying position, m
X_{Total}^{SD}	Standard deviation of the impacts points, m
δ_b	Projectile in-bore yaw
$\theta_{\mathrm{Gun}}^{\mathrm{Error}}$	Cant angle error of gun mounts in the azimuth plane, deg
ρ_A	Atmospheric air density, kg/m^3
$\dot{\psi}_{\mathrm{Gun}}$	The angular velocity of the cant angle of gun mounts in azimuth plane, rad/s
$\dot{\psi}_{\mathrm{Gun}}^{SD}$	Std Deviation of the angular velocity of the cant angle of gun mounts in azimuth plane, rad/s

AGL	Automatic Grenade Launcher
ATC	Aberdeen Test Center
CASW	Close Area Suppression Weapon System
CF	Canadian Force
CFB	Canadian Force Base
FCS	Fire Control System
GPMG	General Purpose Machine Gun
LRF	Laser Range Finder
LUVW	Light Utility Vehicle Wheeled fleet
MPI	Mean Point of Impact
NATO	North Atlantic Treaty Organization
PHit	Probability of hit
PMO	Project Management Office
PRODAS	PROjectile and Design and Analysis System
QE	Quadrant Elevation
RFP	Request For Proposal
RWS	Remote Weapon Station
SD	Standard Deviation
SOR	Statement of Operational Requirements

TAPV	Tactical Armoured Patrol Vehicle
VPS	Vehicle Performance Specifications

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A probability of hit (PHit) methodology has been developed to characterize the overall performance of the C6 General Purpose Machine Gun (GPMG) and 40 mm Automatic Grenade Launcher (AGL) Integrated on a Remote Weapon Station (RWS) Mounted on a Tactical Armoured Patrol Vehicle (TAPV) Platform. The methodology takes into account four (4) different scenarios (static/moving vehicle to engage a static/moving target) to develop an error budget of the weapon system.

The error budget analysis breaks down the total dispersion, i.e., the standard deviation (SD) of the impact point position, into four (4) main error sources: weather, gun, projectile and the Fire Control System (FCS) Dispersion. The weather dispersion can be developed to see the individual contributions of the standard deviation of the wind speed, atmospheric temperature and atmospheric pressure. The Gun dispersion can be developed to see the individual contributions to the standard deviation of the gun support and the gun barrel. The projectile dispersion can be developed to see the individual contributions to the standard deviation of the ammunition dispersion, muzzle velocity, drag-mass ratio and tracer effect. The FCS dispersion can be developed to see the individual contributions to the standard deviation of the gun laying, target tracking, vehicle movement and mutual interaction effects.

The PRODAS (PROjectile and Design and Analysis System) budget error and simulation package were used to model the weapon system performance for different firings conditions. The experimental data from the static/moving vehicle against static/moving target scenarios necessary to validate the PRODAS modeling is being obtained in the CFB (Canadian Forces Base).

Une méthodologie de probabilité d'impact (PHit) a été développée pour caractériser la performance globale de la mitrailleuse polyvalente (GPMG) C6 et du lanceur automatique de grenade (AGL) 40 mm intégrés sur un système d'armement télécommandé (RWS) monté sur un véhicule de patrouille blindé tactique (TAPV). La méthodologie prend en considération quatre (4) scénarios différents (véhicule statique/en mouvement qui engage une cible statique/en mouvement) pour le développement du budget d'erreur du système d'arme.

L'analyse du budget d'erreur décompose la dispersion totale, soit la déviation standard (SD) de la position du point d'impact, en quatre (4) principales sources d'erreur : Météo, l'arme, projectile et le système de conduite de tir (FCS). La dispersion météo peut être développée pour analyser les différentes contributions individuelles de la déviation standard de la vitesse du vent, de la température atmosphérique et de la pression atmosphérique. La dispersion de l'arme peut être développée pour analyser les différentes contributions individuelles de la déviation standard du support et de l'âme de l'arme. La dispersion du projectile peut être développée pour analyser les différentes contributions individuelles de la déviation standard de la dispersion de la munition, de la vitesse initiale du projectile, du rapport traînée-masse et l'effet du traceur. La dispersion du FCS peut être développée pour analyser les différentes contributions individuelles de la déviation standard du support de l'arme, du système de pointage de l'arme, le mouvement du véhicule et les effets d'interactions mutuelles.

L'ensemble numérique de simulation et de calcul du budget d'erreur PRODAS (PROjectile and Design and Analysis System) ont été utilisés pour la modélisation de la performance du système d'armement pour différentes conditions de tirs. Les données expérimentales provenant des scénarios véhicule statique/en mouvement qui engage une cible statique/en mouvement nécessaires pour valider la modélisation PRODAS seront obtenus à la BFC (Base des Forces canadiennes).

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TAPV; Error budget; PRODAS;Ground-to-Ground;Ballistics;C6 GPMG;40 mm AGL

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